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Energy Efficient Stol Transport Aircraft: Phase II

Summary Report

Prepared for the
Transportation
Development Centre
Transport Canada

March, 1982

DHC-TDC 81-1

ENERGY EFFICIENT STOL TRANSPORT AIRCRAFT:

PHASE II SUMMARY REPORT

A STOL Aircraft Research Report
Prepared under Sponsorship of

TRANSPORTATION DEVELOPMENT CENTRE

in
Fulfillment of Contract
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THE DE HAVILLAND AIRCRAFT OF CANADA, LIMITED

Disclaimer:

The contents of this report reflect the views of the contractor and not necessarily the official views or policies of the Transportation Development Centre.

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17. Abstract

The report summarizes work by De Havilland Canada in Phase II of a program to improve the energy efficiency of future STOL transport aircraft.

Airfoils of 21% and 13% maximum thicknesses were designed suitable for a propeller. The airfoils were members of a family including a 6% thick airfoil studied in Phase I. Two-dimensional tests of the airfoils at the National Aeronautical Establishment (NAE) showed significant improvements in maximum lift, best lift/drag ratio and minimum drag relative to conventional propeller airfoils. These improvements will increase propeller efficiencies by 1 - 3% and propeller blades can be made narrower and lighter. Tests with a glove simulating deicer boots and roughness equivalent to paint showed that either source could lead to significant penalties (1 - 2%) in efficiency.

A new wing tip airfoil was designed with reduced aft camber to reduce aileron hinge moments. Tests showed the hinge moment coefficient b_o was reduced to 75% of current airfoils. However the effects of incidence and deflection on hinge moments remained similar to current airfoils, so aerodynamic balance requirements would not be altered. At zero aileron deflection the maximum lift coefficients were found similar to current aft cambered airfoils, while at 30^o deflection an improvement of 12% in C_{Lmax} indicated some potential for smaller ailerons or more highly tapered wings.

Recommendations are made for the R & D in the Phase III of the program.

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17. Résumé

La rapport est un sommaire de la phase II de l'étude par de Havilland Aircraft du Canada pour améliorer le rendement énergétique de l'avion de transport ADAC projeté. Des profils aërodynamiques, ayant les épaisseurs maximales de 21% et de 13%, ont été conçus pour une hélice. Ces profils sont unis dans un ensemble comprenant un profil d'une épaisseur de 6%, sous étude dans la phase I. Ils ont été soumis à des essais bidimentionnels à l'NAE, démontrant des améliorations significatives dans la poussée aërostatique maximale, dans une meilleure finesse et en trainée réduite en regard des profils conventionnels d'hélices. Ces améliorations augmenteront le rendement des hélices de 1% a 3%, dont les pales seront plus restreintes et plus réduites. Les essais avec une couche uniforme de grains grossiers équivalente à la peinture ont démontré qu'aucune de ces modifications ne pouvait conduire à des défauts (1% à 2%) de rendement. Un nouveau profil aërodynamique pour l'extrémité d'une aile a été conçue avec une cambrure arrière réduite pour diminuer les de charnière de l'aileron. Les essais ont montré que le coefficient du de charnière b_o a été réduit à 75% de celui des profils aërodynamiques courants. Cependant, les effets de l'incidence et du bracage sur les de charnière demeuraient similaires aux dits profils, de telle sorte que les exigences d'un équilibrage aërodynamique n'étaient pas altérées. Avec un bracage de l'aileron à 0^o, les coefficients de la poussée aërostatique maximale étaient similaires aux profils aérodynamiques courants d'une cambrure arrière, alors qu'avec un bracage à 30^o, l'amélioration de 12% de la portance maximale a démontré des potentialités pour des ailerons plus petits ou des ailes plus trapézoïdales. Des recommendations sont soumises vers la recherche et le développement pour la troisième phase du programme.

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SUMMARY

This report summarizes work undertaken by De Havilland Canada in Phase II of a jointly funded contract with Transportation Development Centre of Transport Canada, to improve the energy efficiency of future STOL transport aircraft.

Two advanced airfoils of 13% and 21% maximum thickness were designed suitable for a STOL propeller. The airfoils were members of a family including a 6% thick propeller airfoil designed and tested in Phase II of this program. The new airfoils achieved maximum lifts and best lift/drag ratios about 30 - 40% greater than conventional propeller airfoils. These improvements will allow propeller blades to be narrower and lighter in weight, and propeller thrust will increase by 1 - 3%. The airfoils were tested with a distributed roughness similar to paint and with a leading edge glove to simulate a deicer boot. It was found that either source increased drag substantially (50 - 100%) which would result in penalties to propeller thrust of 2 - 4%.

A new wing tip airfoil was designed having reduced aft camber to diminish aileron hinge moments and possibly reduce aerodynamic balance requirements. Tests showed the hinge moment coefficient b_o was reduced about 25% relative to current airfoils. However the effects of incidence and aileron deflection on hinge moments were relatively unaffected so balance requirements would not be reduced. The maximum lift coefficients with zero aileron deflection were similar to current aft loaded airfoils, while at 30^o deflection an increase in $C_{L_{max}}$ of 12% indicated a potential for smaller ailerons or more highly tapered wings.

As a result of these findings a program is recommended for Phase III R & D. This includes work on leading edge devices to enhance maximum lift and reduce wing size. Further work on propellers is suggested which will complete the family of propeller airfoils by testing a new 4% thick section. Work is also recommended which studies the integration of a turboprop nacelle and exhaust with a wing to reduce interference penalties in drag and thrust recovery.

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1. INTRODUCTION

De Havilland Canada has completed the second Phase of a jointly funded R & D program with Transportation Development Centre, which is aimed at improving the energy efficiency of future STOL transport aircraft. Three tasks were undertaken in this Phase:

- the design and test of a 21% thick airfoil suitable for the inner part of a STOL propeller;
- the design and test of a 13% thick airfoil suitable for the middle region of a STOL propeller;
- the design and test of a wing tip airfoil and aileron suitable for a propeller driven STOL transport.

This report summarizes the objectives for each of the above tasks and highlights the achievements of this phase. Based on the results of the two phases completed to date, recommendations are made for the third phase of R & D in this program.

2 REVIEW OF RESULTS

2.1 Task I Design and Test of a 21% Thick Propeller Airfoil

The objectives were to design a new 21% thick airfoil suitable for 20 - 30% of the maximum radius of a STOL propeller. Although this region of a propeller does not contribute much to overall propeller efficiency, high performance is still needed as it imparts a pressure rise to the engine inlet flow which boosts engine performance significantly. A suitable airfoil needs to have high maximum lift for takeoff performance, combined with low drag throughout the wide range of local flow conditions encountered between climb and cruise speeds, Figure 1 (page 15).

The airfoil geometry is shown in Figure 2 (page 16) along with other propeller airfoils designed in this program. It was designed to encourage laminar flow over the first 30% of chord to reduce drag, while still retaining satisfactory performance with fully turbulent boundary layers such as might be caused by roughness from surface damage in service. The significant design features include a blunt nose, high forward camber combined with a little aft camber, and a blunt trailing edge 0.5% chord deep to aid manufacture. To obtain conditions favourable to laminar flow, the airfoil upper surface develops a "rooftop" extending over 30% of chord at a lift coefficient of 1.5 and this is followed by a moderately concave pressure recovery which avoids early flow separation and reduces drag.

The airfoil was tested in the National Aeronautical Establishment 0.38 m x 1.5 m two-dimensional wind tunnel at Mach numbers from 0.2 to 0.6 and Reynolds numbers from 1.3 million to 6 million. Contrary to normal trends the highest performance was found at the lowest Reynolds numbers tested. It appears that turbulence in the wind tunnel increases with Reynolds number, causing earlier transition, thicker boundary layers and increased drag. At representative takeoff conditions Reynolds numbers are about 1.5 million and Mach numbers about 0.2, Figure 1 (page 15), and the airfoil achieved maximum lift coefficients about 1.7, best lift/drag ratios about

130 and minimum drag coefficients about 0.009. Increasing Reynolds number to 3 million reduced maximum lift and best lift/drag ratio by about 10%, while minimum drag was unchanged, Figure 3 (page 17). The performance achieved, even at the higher test Reynolds number, was substantially better than tests elsewhere on thick propeller airfoils.

The airfoil stalled quite abruptly at all test conditions, Figure 4 (page 18), and it appeared that the pressure recovery on the upper surface was made too concave for a progressive stall, Figure 5 (page 19). This adverse behaviour may not be of concern on an actual propeller as it is known airfoil performance usually improves due to centrifugal effects stabilizing the boundary layers.

Tests were also made with the airfoil covered with a taped on roughness giving a roughness similar to paint of 120 - 160 micro inches. This increased drag about 40% and reduced maximum lift about 18% relative to the smooth airfoil, Figure 3 (page 17). A leading edge glove was fitted similar to a deicer boot with aft facing steps at 25% chord. This caused even larger penalties and drag increased about 65%, while maximum lift reduced about 20% relative to the smooth airfoil.

Calculations of propeller performance show that doubling airfoil drag typically reduces thrust by 4%, so the penalties observed for either roughness or deicer boots correspond to losses of 2 - 3% in propeller thrust. There is now experimental evidence from complete propeller tests in other DHC R & D programs that such penalties occur in practice. This background knowledge has been of considerable value to DHC in ensuring that realistic allowances are made for such effects when propeller manufacturers compute performance.

2.2 Task II The Design and Test of a 13% Propeller Airfoil

The objectives of this task were to design and test a new propeller airfoil of 13% maximum

thickness, suitable for use at about 50% of the maximum radius on a STOL propeller. This part of a propeller is important at all operating conditions, so the airfoil needs high maximum lift for takeoff thrust and low drag at all other conditions to give high efficiency. Also the airfoil shape has to be a member of a family including the airfoils at other stations, so that the entire propeller blade surface varies smoothly for ease of manufacture.

The airfoil is shown in Figure 2 (page 16). The shape was obtained by combining the camber lines and thickness distributions of the previously designed propeller airfoils of 6% and 21% thickness, Figure 2 (page 16). The combination of camber and thickness finally selected was found by systematically varying parameters controlling the mixture, then analyzing the performance of the resulting airfoil at typical takeoff and cruise conditions to find the best shape. The selected geometry has a blunter nose than conventional propeller airfoils to enhance maximum lift, while the maximum thickness was made quite well aft (35% chord) to encourage laminar flow at cruise and obtain low drag. The airfoil has a blunt trailing edge of 0.5% chord depth to ease manufacture without unduly penalizing drag. The airfoil was tested in the National Aeronautical Establishment 0.38 m. x 1.5 m. two-dimensional wind tunnel. At typical takeoff conditions of 0.40 Mach number and 2.5 million Reynolds number, Figure 1 (page 15), the maximum lift was $C_{L_{max}} \approx 1.45$, Figure 7 (page 21). This value was about 30% better than conventional propeller airfoils but about 10% less than new designs such as the Dowty-ARAD type which have considerably greater camber. As a consequence the propeller blade chords needed for equal takeoff thrust will be about 20% less than conventional airfoils but about 10% more than the ARAD type.

In the climb local Mach numbers are typically 0.4 to 0.5 and the lift coefficients about 1.0 at the 50% radius, Figure 1 (page 15). For these conditions the lift/drag ratios were 100 - 110

compared with values about 75 for either conventional airfoils or the Dowty-ARAD type, Figure 7 (page 21). Such improvements are estimated to increase climb thrusts by 1 - 1½% and in climb limited situations the resulting increase in gross weight available will increase payloads by 4 - 5%.

At cruise the local Mach numbers are about 0.55 and lift coefficients fall to 0.4, Figure 1 (page 15). At these conditions the low camber of the DHC airfoil becomes an advantage and lift/drag ratios of about 50 were achieved compared with 30 for an ARAD airfoil, and 40 for a conventional airfoil, Figure 7 (page 21). These improvements indicate that increases in cruise efficiency 1 - 2% are feasible from the DHC airfoils.

The airfoil was also tested covered with tape roughness and a simulated deicer boot and the effects on performance are summarized in Figure 6 (page 20). The penalty in maximum lift was found insignificant for either type of treatment. The penalties in drag and best lift drag ratio were similar for both treatments, and typically the best lift/drag ratio reduced by 30%, while minimum drag increased 30%. The drag penalties of either roughness or boots would correspond to losses in propeller thrust of 1 - 1½% and reductions in payload about three times as large.

2.3 Task III Design and Test of a Wing Tip Airfoil

The objective of this task was to design and test a new airfoil suitable for the wing tip of a STOL transport aircraft having manually operated ailerons. The design of such an airfoil involves various considerations including the need for significantly higher maximum lift and stall incidences than the wing root airfoil, to protect the wing tips from stall and to maintain lateral control effectiveness. Also the wing tip airfoil should stall progressively without an abrupt lift loss, to prevent an uncontrollable wing drop in the event of tip stall during turning or yawing flight. Lastly it is desirable to increase aileron effectiveness so that the spanwise extent of the

ailerons can be minimized, allowing flap span to be increased for high lift.

The airfoil was designed using inverse methods available at DHC and the geometry of the airfoil and aileron are shown in Figure 8 (page 22). The upper surface and nose were carefully shaped to obtain high lift without using any leading edge droop which could have lead to increased cruise drag. Unlike currently used airfoils there is very little aft camber as it was desired to reduce aileron hinge moments, possibly allowing smaller aerodynamic balances to be used and also increasing aileron effectiveness. The airfoil maximum thickness was made 14% chord to avoid undercamber on the main body of the airfoil, which was considered undesirable.

The airfoil and aileron were tested in the NAE 0.38 m. x 1.5 m. two-dimensional wind tunnel over an appropriate range of test conditions. It was found that the lift curve of the tip airfoil was well matched to the lift curve of the 21% thick wing root section tested in Phase I, Figure 9 (page 23), and there were satisfactory margins in maximum lift and stall incidence. The aileron effectiveness as measured by the maximum lift available from aileron deflection is compared with a current airfoil having higher aft camber in Figure 10 (page 24). At the maximum aileron deflection of 30^{o} the new airfoil gave 12% more maximum lift, indicating some potential for reducing aileron size or using a more highly tapered wing planform.

The use of reduced aft camber resulted in an aileron hinge moment coefficient b_0 which was about 25% less than current airfoils. However the effects of incidence and aileron deflection on hinge moment coefficients b_1 and b_2 were found similar to current airfoils, so the aerodynamic balance requirements would not be significantly altered. (Figure 11, page 25).

3. CONCLUSIONS

3.1 Task I Tests of a 21% Thick Propeller Airfoil

1. The best performance was achieved at the lowest Reynolds numbers tested (1.3 million). A maximum lift coefficient of 1.75 was recorded indicating good static thrust performance, while the best lift/drag ratios of 130 indicated good climb performance. The airfoil drag at cruise lift coefficients about 0.4 was about 0.008 which indicates good cruise performance is attainable.

2. At higher Reynolds numbers performance deteriorated which was contrary to normal trends. This appeared due to increasing wind tunnel turbulence shortening the runs of laminar flow on the airfoil, leading to increased drag and earlier flow separation at high lift. At 3 million Reynolds number the maximum lift/drag ratios fell to about 90, and minimum drag increasad to about 0.010.

3. The airfoil had an abrupt stall which it had been hoped to avoid by using less concavity in the upper surface pressure recovery than the limiting Stratford shape. It is uncertain whether this would degrade static thrust on an actual propeller due to the stabilizing effects of rotation on boundary layers usually observed on propellers.

4. Tests with surface roughness typical of paint and with a leading edge glove representing a deicer boot showed large penalties. Either source degraded the maximum lift to about 1.4 and increased drag up to 65%. Such penalties would reduce propeller thrusts by 2 - 3% and they serve to emphasize the importance of achieving a smooth finish and main-

taining close control of the profile during manufacture.

3.2 Task II Tests of a 13% Thick Propeller Airfoil

1. Constructing the 13% thick airfoil by combining the camber lines and thickness distributions of the 6% and 21% thick airfoils lead to a shape with excellent performance characteristics.
2. The airfoil achieved maximum lifts about 20% greater than conventional propeller airfoils, but about 10% less than the more highly cambered ARAD airfoils. Thus for equal takeoff performance the new airfoil would need blade widths about 20% less than conventional airfoils or 10% more than the ARAD type.
3. At climb conditions the airfoil achieved lift/drag ratios about 40% better than either conventional airfoils or the ARAD type. Such improvements should increase climb thrusts by 1 - 1½% and allow payload increases of 4 - 5% when gross weight is climb limited.
4. At cruise conditions the lift/drag ratios were about 25% greater than conventional airfoils and 75% better than the ARAD type. Such improvements should increase cruise thrusts by 1 - 2% or permit similar savings in power required and fuel flow.
5. Tests with surface roughness typical of paint and a simulated deicer boot showed negligible effects on maximum lift. Drag and lift/drag ratios were penalized about 30% by either source. Such penalties correspond to reductions in thrust about 1 - 1½% from either source, and emphasize the importance of a smooth finish and careful manufacture of the profile.

3.3 Task III Tests of a Wing Tip Airfoil

1. The airfoil was designed with reduced aft camber to reduce aileron hinge moments. The tests showed the hinge moment coefficient b_o was 25% less than current airfoils with greater aft camber. It was found the effects of incidence and aileron deflection on hinge moments remained similar to current airfoils, so there would not be significant changes in aerodynamic balance requirements.
2. The maximum lift with aileron undeflected was found to be similar to current airfoil values, while with 30^o deflection the $C_{L_{max}}$ was 12% greater. This indicates some potential for smaller ailerons, or higher wing taper than currently used.
3. The airfoil had maximum lift and stall incidences which gave satisfactory margins relative to the 21% thick airfoil tested in Phase I. Also the airfoil exhibited the progressive type of trailing edge stall, desirable for a wing tip.

4. RESEARCH RECOMMENDATIONS

As a result of the work accomplished in Phases I and II and other complementary programs on-going at DHC, the following items are recommended for study in Phase II:

1. Continue work on propeller airfoils. An airfoil of 4% thickness should be tested which will be suitable for a propeller tip. This will complete the family of propeller airfoils and allow a complete propeller to be designed.
2. Continue the work on wing airfoils, considering next the benefits of leading edge devices to delay stall and increase maximum lift.
3. Commence a new item concerning the integration of a turboprop powerplant with a wing to obtain the best overall performance.

5. APPLICATION OF RESULTS

This program has resulted in new technology airfoils for wings and propellers which show considerable promise. In particular the work on propeller airfoils has been of immediate value to DHC for assessing the claims of the manufacturer of the DHC-8 propeller. The results of this program will be included in on-going project studies of future DHC aircraft and it is intended to exploit the airfoils, or developments thereof, at the earliest possible apportunity.

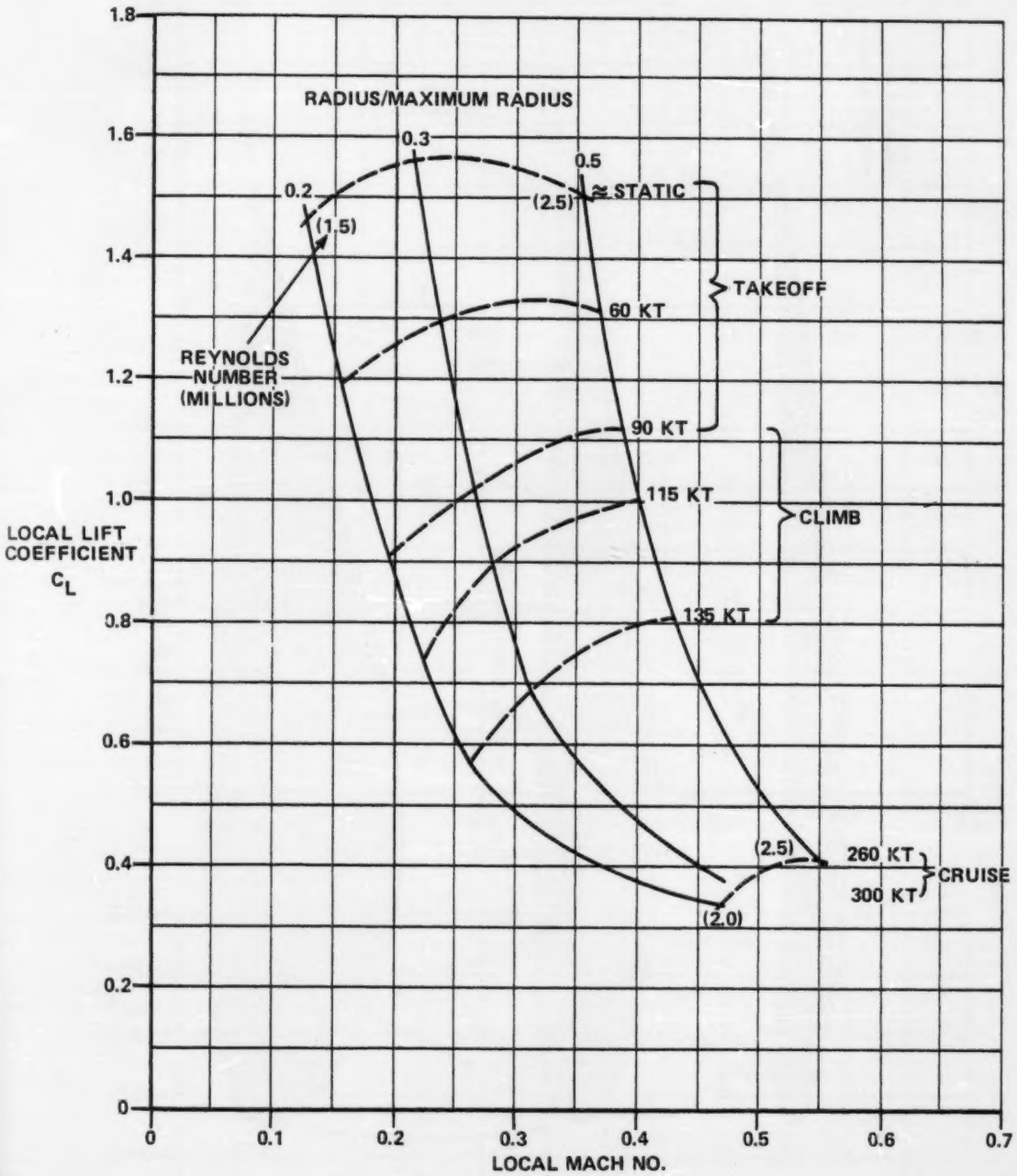


FIGURE 1 LOCAL OPERATING CONDITIONS ON A STOL PROPELLER

FIGURE 2 DHC PROPELLER AIRFOIL DESIGNS

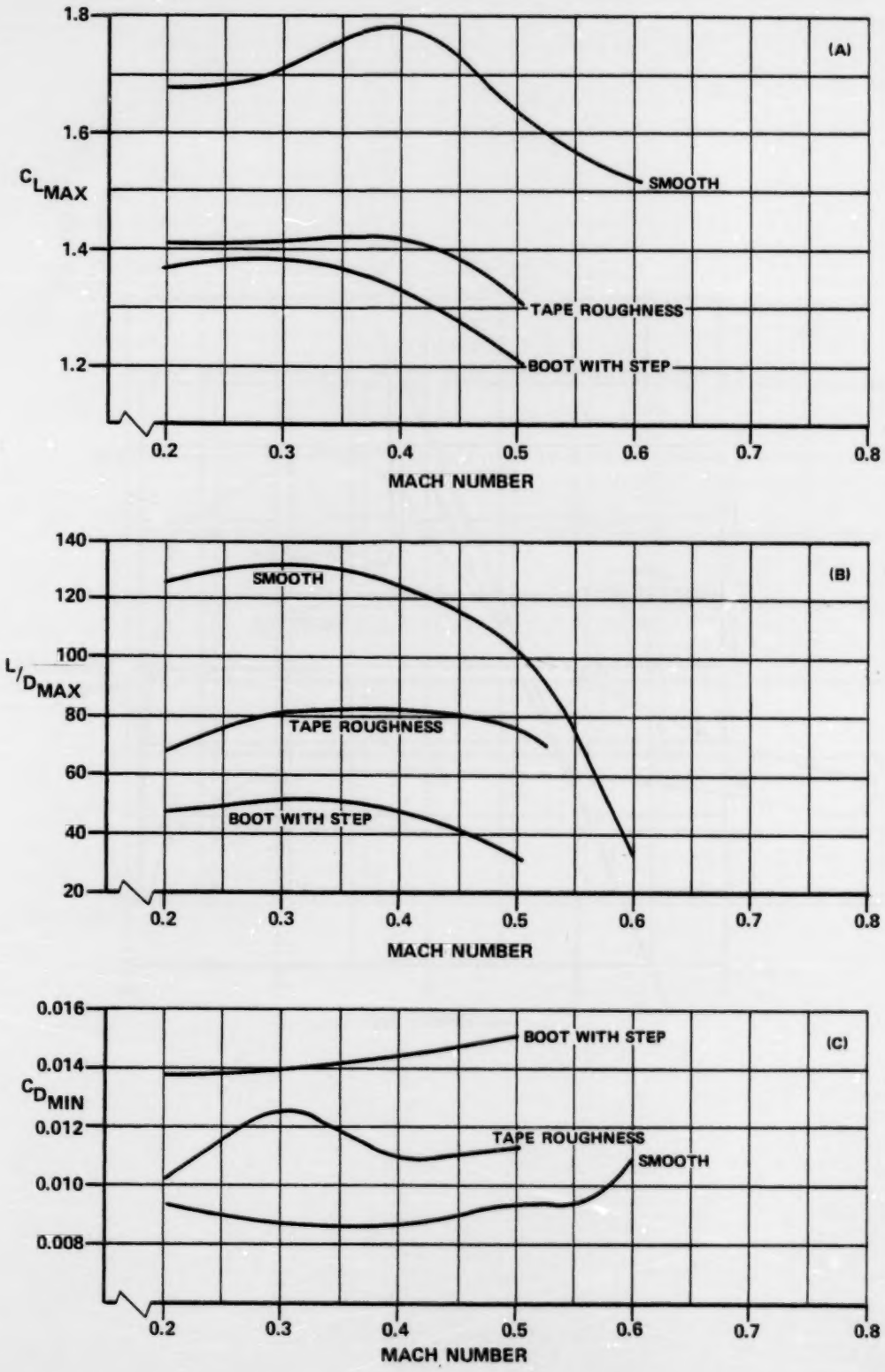


FIGURE 3 INFLUENCE OF AIRFOIL FINISH ON PERFORMANCE OF 21% THICK PROPELLER SECTION

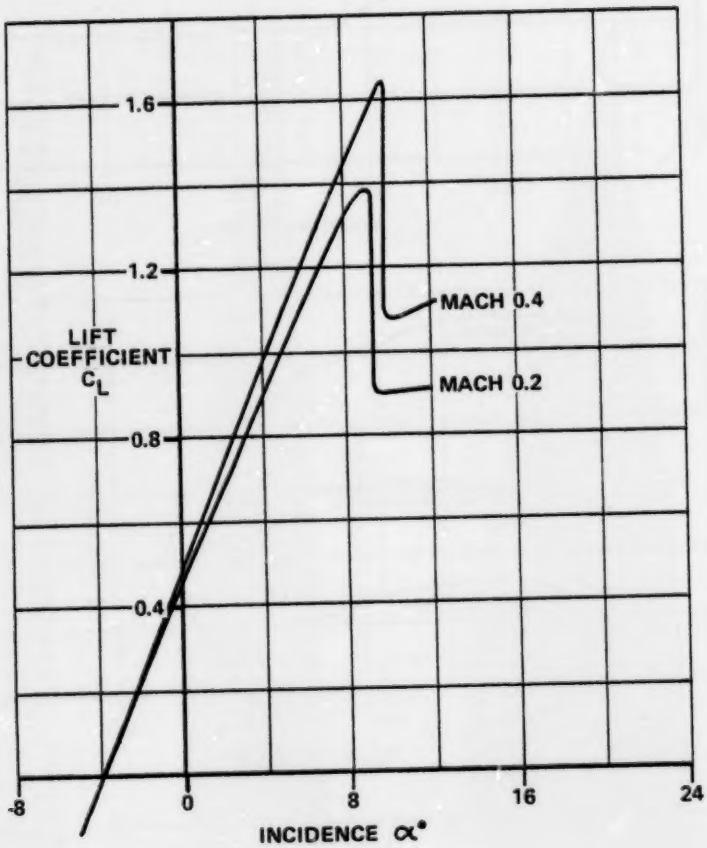


FIGURE 4 LIFT CURVE OF 21% THICK PROPELLER AIRFOIL AT 3 MILLION REYNOLDS NUMBER

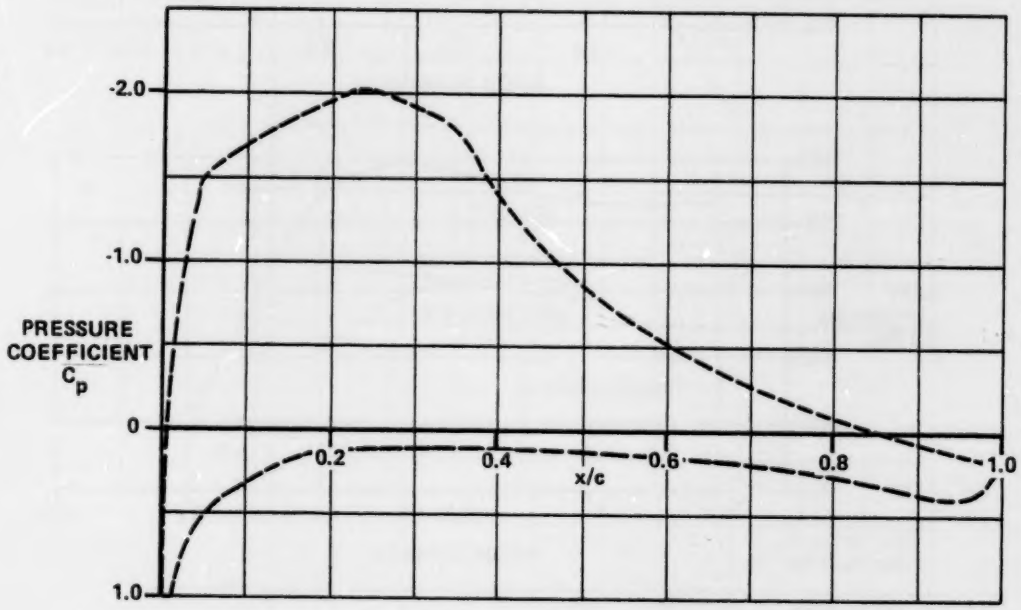
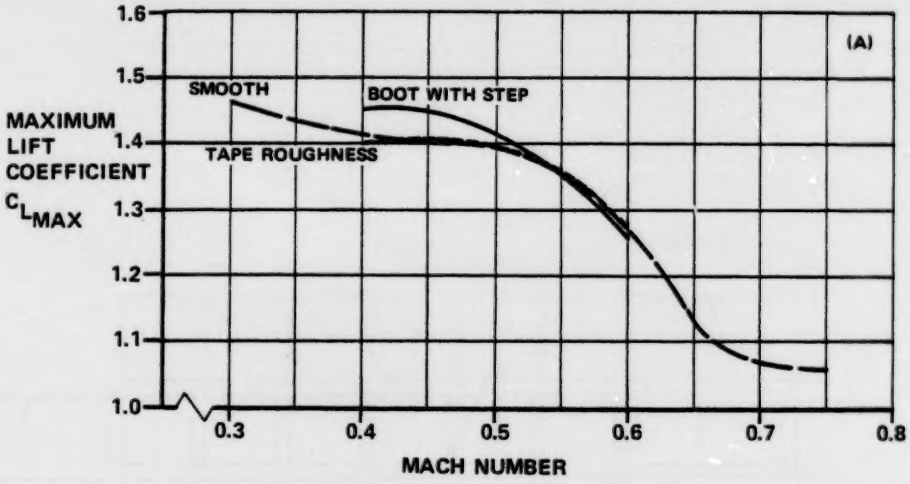
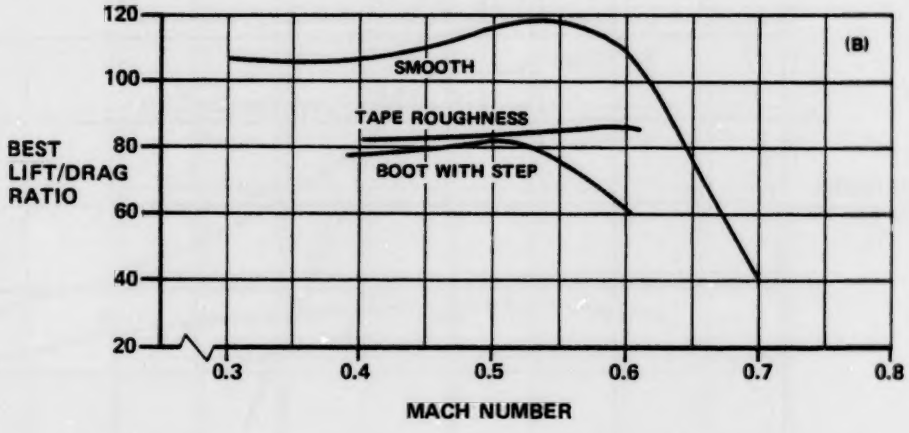


FIGURE 5 PRESSURE DISTRIBUTION ABOUT 21% THICK PROPELLER AIRFOIL AT C_L = 1.15





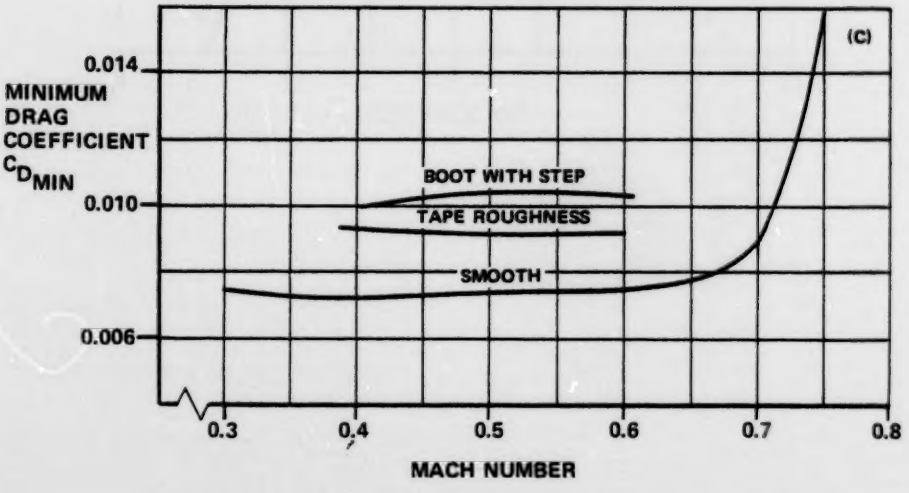


FIGURE 6 INFLUENCE OF AIRFOIL FINISH ON PERFORMANCE OF 13% THICK PROPELLER SECTION

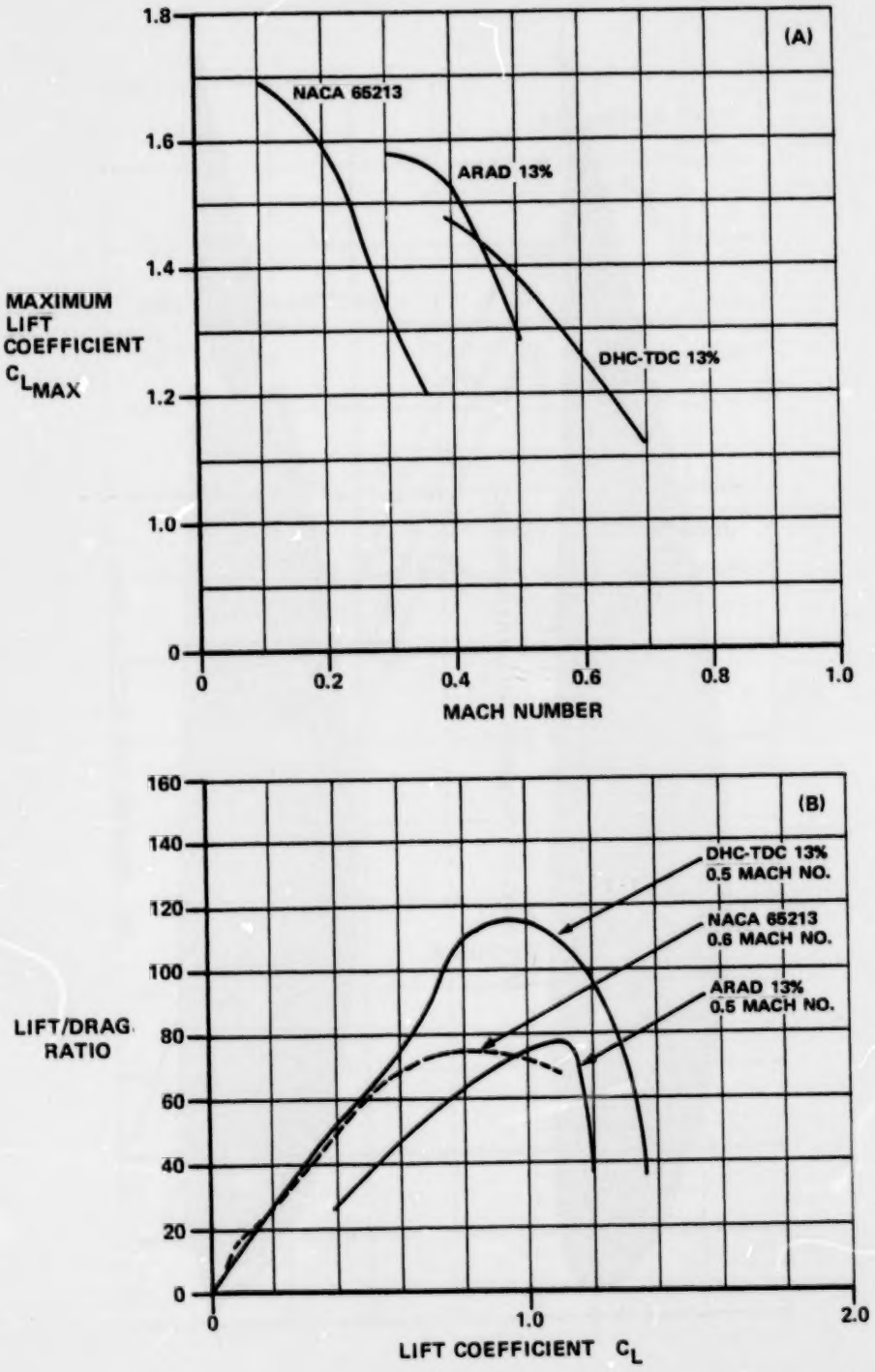


FIGURE 7 COMPARISON OF PROPELLER AIRFOIL PERFORMANCE IN SMOOTH CONDITION

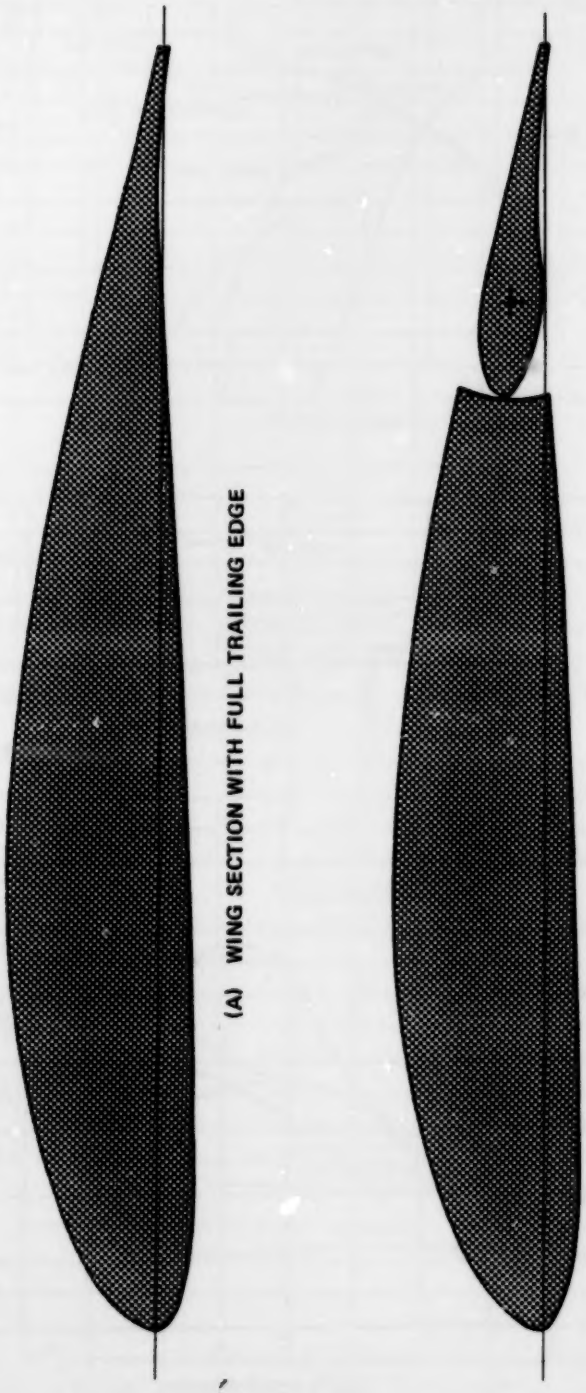


FIGURE 8 DHC-TDC 14% THICK WING TIP AIRFOIL

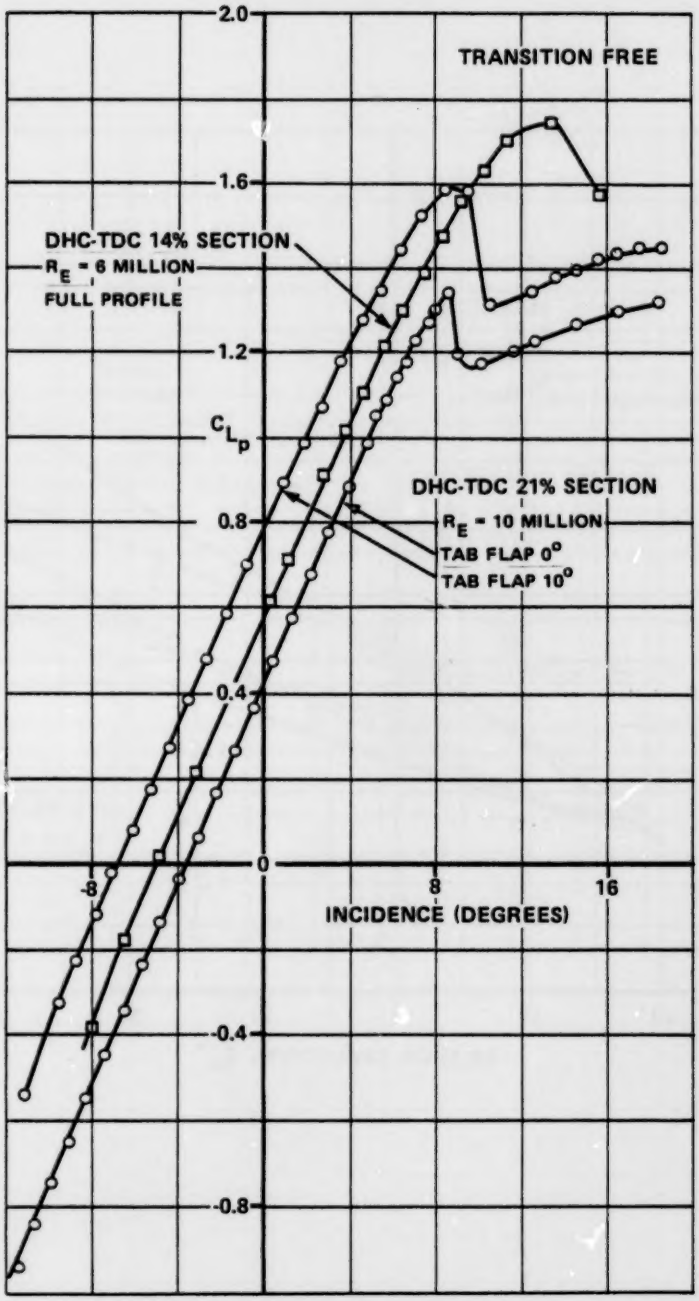


FIGURE 9 COMPARISON OF LIFT CURVES AT M = 0.2

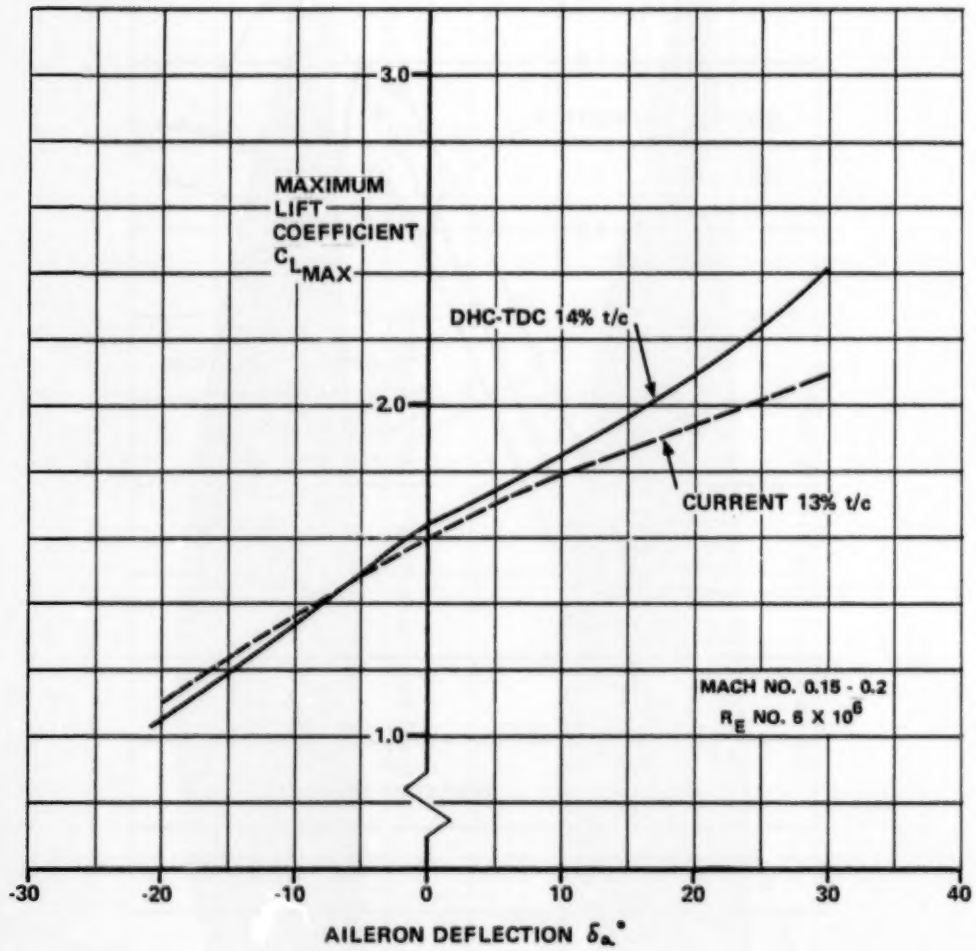


FIGURE 10 COMPARISON OF MAXIMUM LIFTS FOR WING TIP AIRFOILS WITH AILERON

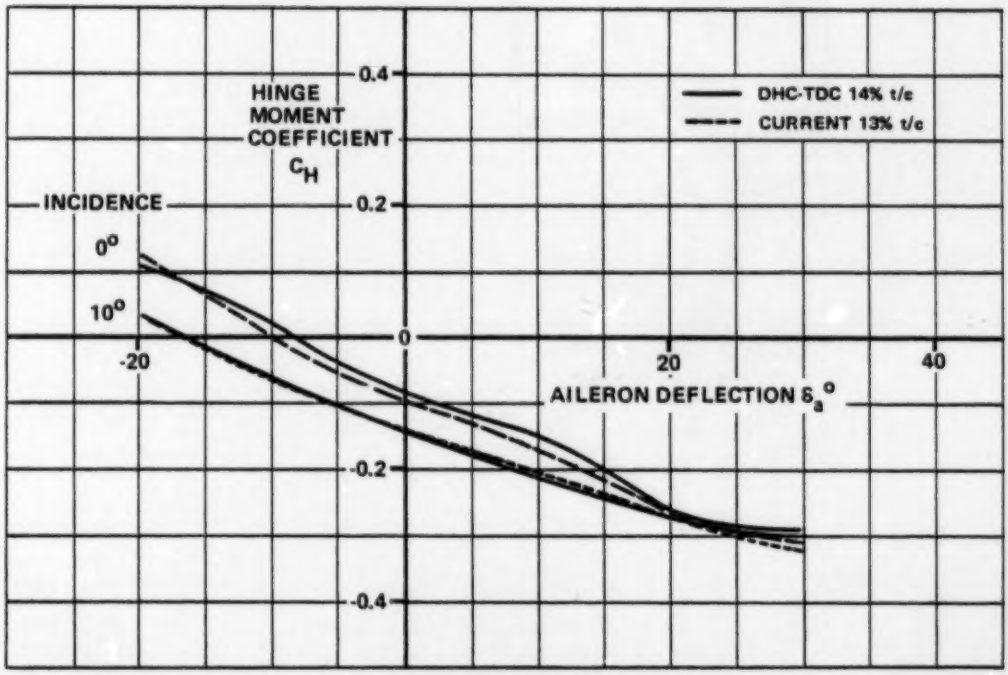


FIGURE 11 COMPARISON OF AILERON HINGE MOMENTS